Melo *et al. Critical Care* (2026) 30:87
https://doi.org/10.1186/s13054-026-05836-x

Critical Care

PERSPECTIVE Open Access

Ultrafiltration in the critically ill patient: a framework for personalized care

Paulo Melo[1,2], Gonzalo Ramírez-Guerrero[3], Ricardo Castro[2], Adrian Wong[4], Eduardo R. Argaiz[5,6], Marlies Ostermann[7], Glenn Hernández[2] and Eduardo Kattan[2,8*]

Abstract

Fluid overload is common after resuscitation in critically ill patients and is independently associated with unfavorable outcomes. Ultrafiltration (UF) during renal replacement therapy is a common strategy to reverse this condition. Nevertheless, the optimal timing, dose, and safety limits remain unclear. Observational studies suggest a U-shaped relationship between net UF rate and mortality, highlighting a narrow therapeutic window. Insufficient UF prolongs exposure to congestion, whereas excessive UF may precipitate hemodynamic instability and tissue hypoperfusion. This phenomenon, often labeled "UF intolerance", lacks a standardized definition and is frequently attributed to intravascular volume depletion alone, overlooking broader cardiovascular and autonomic mechanisms.

This perspective synthesizes the physiological effects and cardiovascular response to ultrafiltration and reframes "ultrafiltration intolerance" as a multidimensional construct determined by four compensatory axes: vascular refilling, cardiac response, venoconstriction/venous capacitance, and systemic arteriolar resistance. We delineate how renal replacement therapy-related factors interact with underlying critical illness to impair these axes and precipitate tissue hypoperfusion. Building on this framework, we (i) argue for proactive, individualized ultrafiltration prescriptions; (ii) propose dynamic predictors that emulate fluid removal to reveal physiologic reserve (iii) outline pragmatic, bedside endotypes of ultrafiltration intolerance: preload dependence, cardiac dysfunction, decreased vascular tone, autonomic dysfunction, and impaired vascular refilling. We propose a holistic framework that emphasizes prevention over rescue and guides tailored ultrafiltration prescription based on endotypes.

Ultrafiltration intolerance in critically ill patients is multifactorial and not solely a problem of volume depletion. A physiology-based, preventive, and personalized ultrafiltration strategy (anchored in dynamic testing, ultrasound-based congestion profiling, and perfusion monitoring) may improve hemodynamic tolerance, decongestion efficacy, and patient-centered outcomes. Prospective studies should validate these concepts to establish evidence-based protocols for personalized ultrafiltration in critical care.

Keywords Fluid overload, Ultrafiltration, Intolerance, Dynamic predictors, Endotypes, Personalized, Critical care

*Correspondence:
Eduardo Kattan
e.kattan@gmail.com

Full list of author information is available at the end of the article

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

SHOUT
SHARE
IT

Background

Fluid overload (FO) following resuscitation of critically ill patients remains a prevalent issue of concern, since it is associated with poor clinical outcomes [1–3] including increased rates of acute kidney injury (AKI) [4], impaired recovery from AKI [5], prolonged need for mechanical ventilation [6] and overall mortality [1, 7–9].

Ultrafiltration (UF), the pressure-driven process that removes fluid during dialysis sessions, is a common strategy to reverse FO in patients with oliguric AKI, with diuretic resistance, or who develop life-threatening complications. In fact, over two-thirds of patients have FO at the onset of renal replacement therapy (RRT) [1, 10]. UF effectively mitigates the severity and duration of FO [11]. Although fluid removal is associated with reduced mortality [12, 13], overall mortality in this population still exceeds 40% [1, 12, 14–16].

Numerous aspects of optimal UF remain unclear, including the ideal timing of initiation, the optimal dosage and UF rate, safety limits to guide these interventions, and the role of adjunctive strategies (i.e. albumin supplementation) [11]. UF is usually prescribed based on body weight (ml/kg/h) to avoid exposing patients to inappropriate rates [17]. Net ultrafiltration (UF^{NET}), defined as the volume of fluid removed from the patient subtracted by volume of fluid infused during dialysis [18],

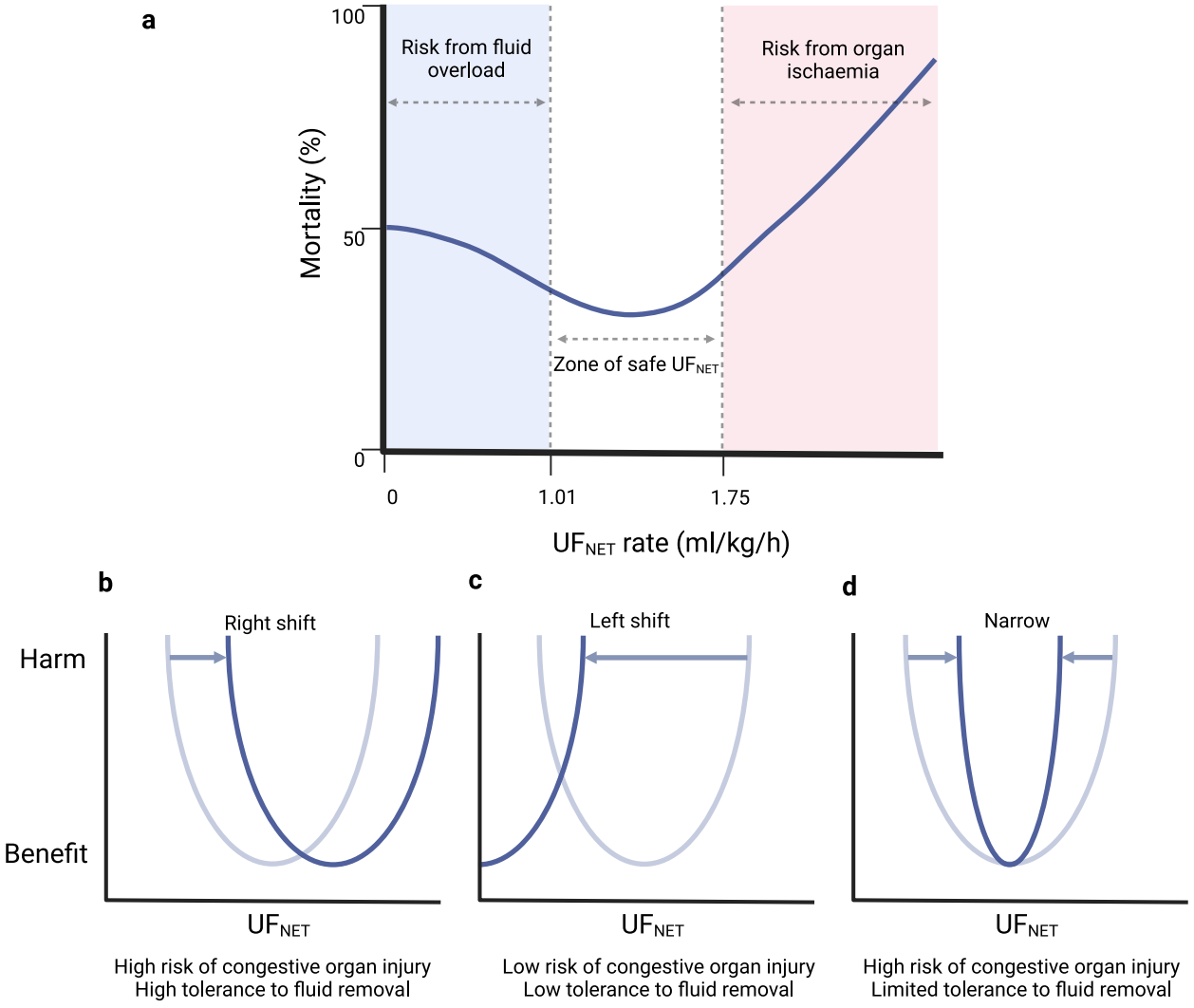

Fig. 1 Association of UF_{NET} rate with mortality in critically ill patients receiving CRRT. Large observational studies have suggested a "U" or "J"-shaped relationship between UF_{NET} on CRRT and mortality. Slow rates (< 1.01 ml/kg/h) expose patients to prolonged periods of fluid overload, whereas fast rates (> 1.75 ml/kg/h) lead to organ ischemia, with both sides increasing mortality. Moderate rates (1.01–1.75 ml/kg/h) are associated with the lowest risk of death (**a**). However, individual patients have different degrees of tolerance to fluid overload and fluid removal as different fluid balance goals. Therefore, the ideal balance between the risk and benefits of UF will vary from patient to patient, potentially shifting this curve both rightward (**b**) and leftward (**c**); furthermore, some patients with particularly challenging hemodynamics will have a narrow therapeutic window for UF (**d**). Figure adapted from Ref. [19]. Created with BioRender.com

has a "U"-shaped relationship with mortality, as suggested by observational studies [16, 19] (Fig. 1).

Excessive fluid removal could result in intradialytic hypotension (IDH) and end-organ hypoperfusion [18, 20]. Hemodynamic instability related to renal replacement therapy (HIRRT) is a common issue at the bedside, present in up to 70% of patients [21–26]. On the other hand, low UF rates extend FO duration, prolonging the need for life support and increasing the risk of adverse outcomes [1, 16, 27].

Clinical heterogeneity, individual critical illness trajectories, and physiological determinants of cardiovascular response to UF, underscore the need to move beyond one-size-fits-all strategies toward individualized therapy. Tailoring UF to the individual patient's needs could aid in avoiding iatrogenic complications and enhance patient-centered outcomes.

In this perspective, we explore the main cardiovascular consequences of UF and the expected physiological response, aiming to refine the paradigm of UF intolerance and its potential endotypes. Finally, we propose a personalized UF strategy based on clinical patterns that are easily identifiable at the bedside, representing a shift from a reactive to a preventive framework.

Physiological effects and response to ultrafiltration: not just low intravascular volume

While UF itself may induce intravascular volume depletion, other factors associated with continuous renal replacement therapy (CRRT), such as thermal stress, electrolyte, and osmolality changes, further contribute to patient instability. This could decrease cardiac output (CO) and peripheral resistance, both of which may be altered by the underlying process of critical illness and exacerbated by RRT [28]. Four main compensatory mechanisms determine the tolerance to fluid removal: vascular refill rate, cardiac response, venoconstriction, and systemic arteriolar resistance [29–31].

During UF, intravascular blood volume may decrease; however, it can remain stable due to vascular refilling. Plasma refilling from the interstitial and intracellular fluid compartments varies among patients; this process relies on the UF rate, degree of FO, plasma oncotic pressure, hydrostatic and osmotic pressure gradients across the capillaries, and endothelial barrier properties [28, 32]. If the UF rate exceeds vascular refill, it may result in intravascular volume depletion [29]; moreover, when refilling is compromised for any reason, even lower rates of UF might still result in hypotension [28].

The cardiovascular response to low preload includes an increase in heart rate (HR), contractility, and peripheral vascular resistance [30, 33–35]. Increases in cardiac contractility may raise CO by increasing stroke volume, influenced by reduced end-systolic volume and quicker myocardial contraction and relaxation, allowing a relative increase in diastolic filling time and end-diastolic volume. Studies during hemodialysis have noted a reduction in myocardial blood flow [36, 37], inducing segmental left ventricular (LV) dysfunction [38]. Lastly, reduced ventricular filling may be intensified by the Bezold-Jarisch reflex triggered by LV emptying, resulting in loss of peripheral sympathetic vasoconstrictor tone, exacerbating hypotension and bradycardia [39]. This phenomenon is more prevalent in individuals exhibiting diastolic dysfunction, often observed in patients undergoing hemodialysis [40] and critically ill [41, 42].

During reduced effective circulating volume and UF, sympathetic activation produces arteriolar and venous constriction, shifting blood from systemic veins to the central cardiopulmonary compartment. Venous capacitance modulation, particularly in skin and splanchnic circulation, depends on active venoconstriction and passive venous recoil [30, 31]. The latter is a consequence of arteriolar vasoconstriction, which reduces regional postcapillary flow and venous pressure (i.e. DeJager-Krogh phenomenon), reducing distending pressure and passive recoil of the venous bed [43]. This mechanism increases venous return, whereas other vascular beds, such as muscle and kidney, exert a minor effect, supporting the central compartment [44]. According to Starling law, precapillary arteriolar constriction also decreases the capillary hydrostatic pressure, favoring vascular refilling [45].

Additional dialysis-associated factors could negatively influence systemic vascular resistance (SVR) and cardiac responsiveness. These include the dialysis solution buffer, changes in plasma sodium, potassium, and calcium levels, acid–base equilibrium throughout hemodialysis, the choice of dialyzer membrane/circuit biocompatibility, and the temperature employed [45].

These four physiological mechanisms maintain hemodynamic stability and perfusion during fluid removal [30, 31]. Those are frequently impaired in critically ill patients with AKI and serve as an indicator of poor physiological reserve [28]. Consequently, a comprehensive understanding of this response and identifying the underlying cause will enable clinicians to provide physiological support, enhancing UF tolerance.

Rationale for personalized ultrafiltration

Excessive fluid removal without tailoring to the individual patient's characteristics may induce IDH [18], reduce microcirculatory blood flow [46, 47], and impair tissue perfusion, thereby contributing to new organ dysfunction (Fig. 2).

HIRRT, an independent predictor of mortality in critically ill patients [48], is usually defined by macrohemodynamic parameters such as IDH or the necessity for therapeutic interventions [49, 50] and is a common

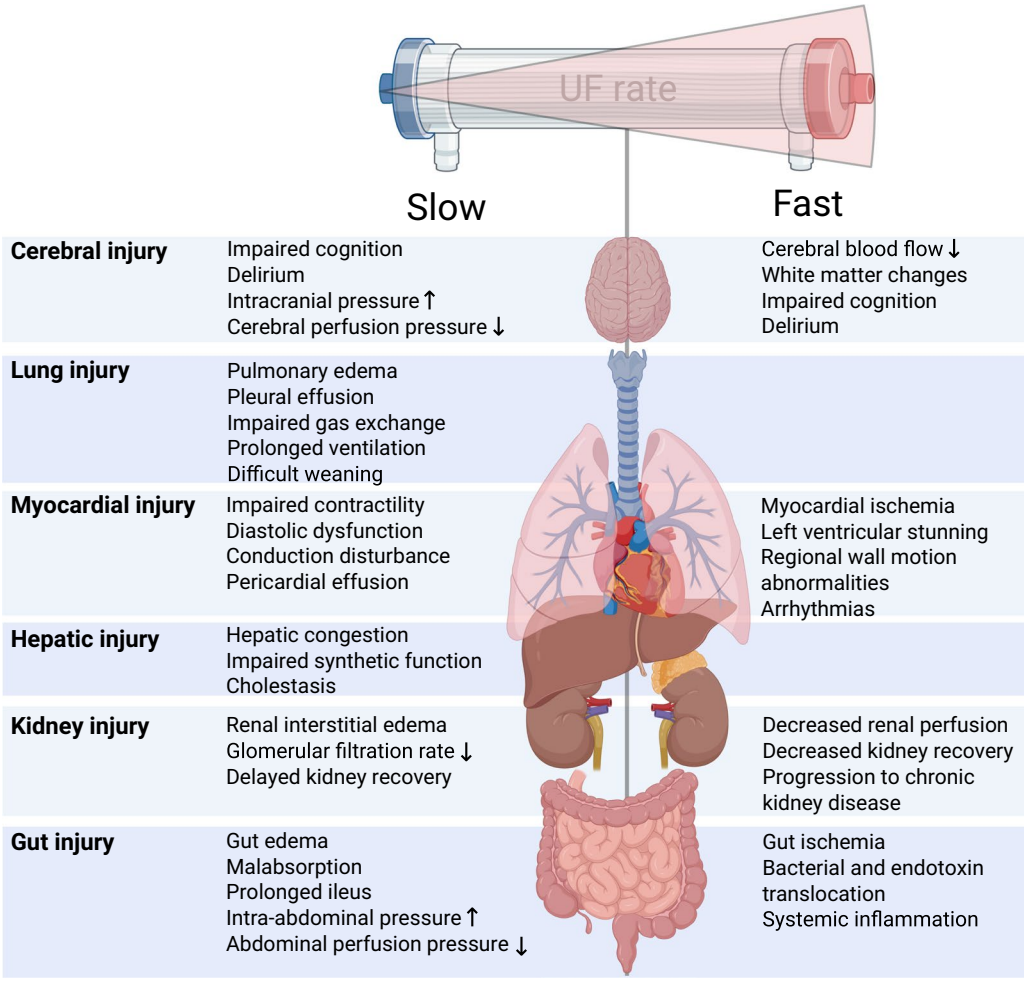

Fig. 2 Potential multisystem injury of fluid overload (left) and fluid removal (right). Insufficient fluid removal can perpetuate the exposure to fluid overload and venous congestion, whereas excessive UF may induce hypoperfusion leading to organ dysfunctions. Created with BioRender.com

complication during all RRT modalities. It occurs in approximately 40–60% of sustained low-efficiency dialysis (SLED) sessions [25, 26] and 19–43% of CRRT [21–24].

During UF, impaired tissue perfusion may occur, especially in organs where perfusion becomes increasingly pressure-dependent, such as the brain. Higher UF rates have been associated with a decline in global and regional cerebral blood flow, which is further correlated with the progression of white matter hyperintensity and cognitive dysfunction [51, 52]. Similarly, patients undergoing CRRT may exhibit myocardial hypoperfusion and stunning with new regional wall motion abnormalities and arrhythmias [53, 54]. Moreover, studies have found decreased splanchnic perfusion during UF due to hepato-splanchnic vasoconstriction [55], which subsequently leads to intestinal ischemia. Lastly, patients with AKI may be susceptible to new ischemic kidney injury during hypotensive episodes because impaired autoregulation predisposes to hypoperfusion and delayed recovery [56, 57].

HIRRT is the main barrier to successful fluid removal, consistently associated with persistent positive fluid balance [58], although the interventions to address IDH are often reactive rather than preventive. Therefore, implementing a personalized UF approach becomes necessary for safe and effective fluid removal, mitigating the risk of organ injury and potentially reducing mortality rates.

Current monitoring and guidance of UF

In contemporary practice, most physicians assess volume status and determine optimal UF using static variables, including macrocirculatory parameters, physical examination for skin edema, fluid balance, body weight, and signs of organ congestion from non-invasive techniques such as chest X-ray. More recently, lung ultrasound (LUS), echocardiography, abdominal vein Doppler, and Venous Excess Ultrasound (VExUS) have been proposed to guide UF, but remain infrequently used [58–60].

As the use of pulmonary artery catheters has declined [61–63], clinicians increasingly rely on ultrasound-based methods to assess hemodynamics. However, ultrasound-derived measurements remain limited by operator dependence, image quality, and variable reproducibility, particularly in ventilated or unstable patients [64–66]. In this context, transpulmonary thermodilution offers a calibrated and operator-independent alternative that provides volumetric and cardiac output measurements that remain technically reliable during RRT; De Laet et al. reported coherent reductions in volumetric indices during UF [67], and Huber et al. confirmed the feasibility of transpulmonary thermodilution during SLED and identified cardiac power index as a predictor of successful fluid removal without hemodynamic deterioration [68]. Given the limitations of each monitoring system, UF tolerance and the individualization of fluid-removal strategies can be assessed through a multimodal approach rather than relying on any single device.

Some dynamic preload-dependence parameters, such as pulse and stroke volume variation, have not been sufficiently validated to predict IDH and show limited predictive accuracy [69]. Given the challenges in predicting individual patient's response to fluid removal, UF is commonly initiated at a low rate and gradually increased to the maximum tolerated level [69, 70]. If UF is not tolerated, it is usually reduced or discontinued, although the underlying mechanism of HIRRT may be unrelated to fluid removal [28].

Signs of adequate perfusion, such as capillary refill time (CRT), have emerged as promising monitoring tools that accurately predict IDH [71]. Bitker et al. pioneered integrating macrocirculation parameters with the onset or extension of mottles to report HIRRT events [72]. Other studies using digital laser doppler flowmetry during UF in CRRT showed that baseline skin blood flow and its early reduction after fluid removal predicted impaired tissue perfusion [73]. These findings underscore the need to refine the HIRRT definition by integrating perfusion metrics into its framework.

Few studies have incorporated all these concepts to guide and monitor UF [74]. Bitker et al. classified hypotension episodes as related or not to cardiac preload using passive leg raising (PLR) with continuous CO measurement. They found that most hypotensive episodes in intermittent hemodialysis were unrelated to preload dependence [75]. The GO NEUTRAL trial demonstrated that, in patients with acute circulatory failure, a UF fluid removal strategy, supported by an advanced hemodynamic protocol utilizing dynamic preload-dependent indices, effectively controlled fluid balance [72]. This approach underscored the value of personalized fluid management and demonstrated the potential of functional hemodynamic monitoring to guide UF in critical care.

Given these considerations, the impact of UF on organ perfusion and its multiple mechanisms underscores the need to accurately predict which patients will develop UF intolerance. Drawing parallels with rational fluid resuscitation, incorporating tests that simulate the hemodynamic disturbance of fluid removal, and identifying individual profiles could enable more tailored interventions and minimize the risks of UF.

Ultrafiltration intolerance in critically ill patients: a theoretical construct

Similar to fluid resuscitation, UF should be regarded as a double-edged sword, exhibiting a narrow therapeutic index [76]. On one side, insufficient fluid removal can perpetuate exposure to FO and venous congestion, whereas excessive UF may induce hypoperfusion, leading to organ dysfunction [77].

Ultrafiltration tolerance currently lacks a standardized or widely accepted definition. Building on the emerging concept of fluid tolerance [77] and extending it to fluid removal, it can be defined as the extent to which a patient can undergo UF without developing hemodynamic instability, tissue hypoperfusion, or new-onset organ dysfunction. Ultrafiltration intolerance, therefore, reflects a limited physiological reserve or an inappropriately prescribed UF.

Dynamic predictors for ultrafiltration tolerance: identifying the physiological reserve

During fluid resuscitation, dynamic predictors of fluid responsiveness allow physicians to identify the position on the Frank-Starling curve. These predictors rely on cardiopulmonary interactions or venous return manipulation. Recently, PLR was used to differentiate preload-dependent from non-preload-dependent mechanisms of UF intolerance [50, 72, 76]. However, as this maneuver creates an immediate transfer of blood from peripheral leg veins to central volume, the mechanisms responsible for HIRRT are not directly identified. To predict UF tolerance optimally, a test should emulate the hemodynamic disturbance associated with fluid removal to trigger a response similar to that experienced during UF. These tests could potentially identify patients likely to tolerate UF during RRT initiation. (Fig. 3).

Dynamic predictors of UF tolerance related to venous return: the passive leg lowering test and ultrafiltration challenge

If a PLR can generate a shift of ± 300 mL from the unstressed to stressed volume compartment, it is plausible to hypothesize that rapidly lowering the legs could produce the reverse effect. Although this concept has not

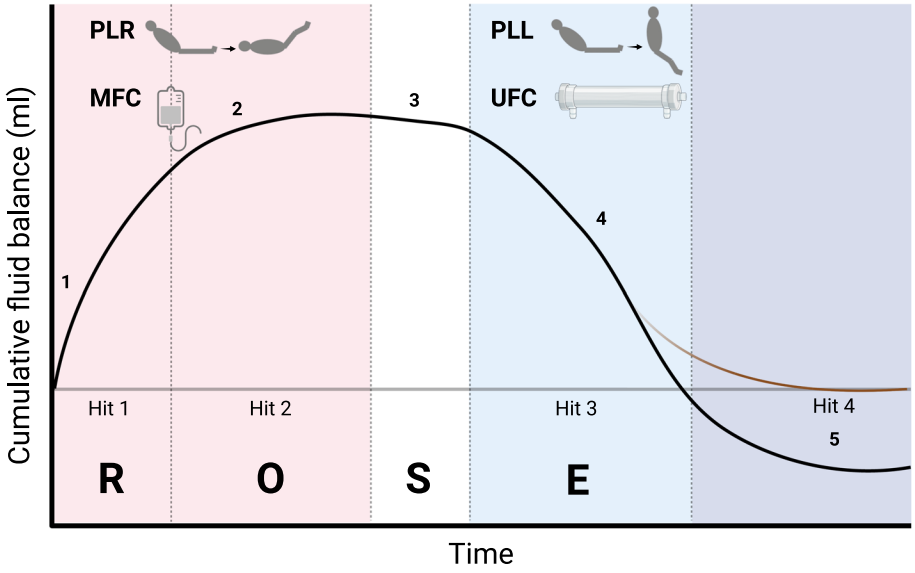

Fig. 3 Four-hit model of shock with patient's fluid volume status over time during five resuscitation phases: Resuscitation (1), optimization (2), stabilization (3), and evacuation (4), followed by a risk of hypoperfusion (5) in case of aggressive fluid removal. During resuscitation and optimization, dynamic predictors of fluid responsiveness (i.e., PLR and MFC) allow physicians to identify which patients require intravenous fluids. Similarly, to optimally predict UF tolerance in patients selected for UF before initiating fluid removal, it is possible to emulate the hemodynamic disturbance associated with fluid removal using a PLL and MUC. Therefore, these potential tests may disclose which patients tolerate UF or not, providing opportunities to tailor therapy and potentially avoid hypoperfusion (5) and future complications. See text for explanation. Figure adapted from Ref. [162]. PLR: passive leg raising, MFC: mini fluid challenge, PLL: passive leg lowering, UFC: ultrafiltration challenge. Created with BioRender.com

been tested, indirect evidence from studies assessing the hemodynamic impact of patient mobilization supports its potential physiological basis. For instance, in elective neurosurgical patients, transpulmonary thermodilution measurements showed that moving from a supine to a 45° seated position significantly reduced arterial pressure, stroke volume, and cardiac index, consistent with a ~ 14% shift of blood volume from the intrathoracic to the extrathoracic compartment, while SVR index increased [78]. Similarly, in patients with acute respiratory distress syndrome, verticalization from a 30° semi-seated position to steeper inclinations significantly decreased stroke volume and CO [79].

The proposed passive leg lowering test would require standardized procedural specifications to minimize confounding factors, similar to those applied for PLR [80]. These include selecting the optimal baseline position and leg movement range to achieve the greatest preload reduction [81]. Also, the most adequate hemodynamic monitoring technique should be identified (i.e. macrohemodynamics or tissue perfusion markers). Finally, potential confounders, such as excessive adrenergic stimulation during the maneuver due to fear, pain, or discomfort, should be considered, as they could independently increase venous return.

While replicating the precise conditions of UF in a clinical environment can be challenging, an UF challenge could represent a feasible alternative. Huang et al. evaluated a blood drainage maneuver ("blood pump-out test") to predict fluid responsiveness in 65 critically ill patients undergoing RRT [82]. After a PLR test to classify responders (CO increase ≥ 10%), patients returned to a semi-recumbent position and underwent drainage of blood at 100 mL/min for about two minutes at the start of RRT. A CO decrease of > 11% during the blood pump-out test predicted fluid responsiveness with 70.9% sensitivity and 76.5% specificity. Although designed to assess fluid responsiveness rather than UF tolerance, this approach supports the concept that small, controlled volume removal can unmask limited hemodynamic reserve. Recently, Biscarrat et al. evaluated the diagnostic performance of a 250-ml UF_{NET} challenge to identify the risk of developing de novo preload-dependence in preload-independent critically ill patients undergoing CRRT [83]. The diagnostic test was performed over 15 min (fast challenge) or 30 min (slow challenge), preceded and followed by a postural maneuver (PLR or Trendelenburg), evaluating preload-dependence using continuous cardiac index relative variations. Their main findings suggest that a decrease in cardiac index of > 9% after the 250-ml UF_{NET} challenge diagnosed de novo preload-dependence with acceptable diagnostic performance, and a postural maneuver inducing a relative variation in continuous cardiac index of ≥ 5% showed good predictive performance to identify patients at risk of becoming preload-dependent. This study highlights the potential of both UF_{NET} challenge and pre-challenge postural maneuvers

Table 1 Dynamic predictors for UF tolerance

Passive leg lowering	Ultrafiltration challenge
Technique based on **virtual** fluid removal challenge	Technique based on **real** fluid removal challenge
Acts as a **reversible** self-fluid removal challenge	Acts as an **irreversible** fluid removal challenge
Should generate a **passage of blood** from the intra-thoracic to the extra-thoracic compartment	**Replicates ultrafiltration** and exposes the individual to the extracorporeal circuit

Clinical characteristics of passive leg lowering and ultrafiltration challenge.

to identify patients at risk of developing preload-dependence and UF intolerance.

To the best of our knowledge, few studies have yet evaluated UF tolerance by performing a UF challenge or applying a passive leg lowering maneuver. The proposed tests rely on real or virtual fluid shifts (Table 1), potentially opening a new avenue for future research.

Potential endotypes of ultrafiltration intolerance

The phenomenon of UF intolerance may arise from multiple and often overlapping mechanisms, all occurring within the framework of a poor physiological reserve to mount an appropriate compensatory response [28]. These mechanisms can be categorized into two distinct groups, RRT factors and patient-related factors. In this section, we will focus on patient-related mechanisms, employing the physiological framework discussed above to propose potential endotypes of UF intolerance (Fig. 4), along with concise tools for their assessment and potential strategies to improve UF tolerance.

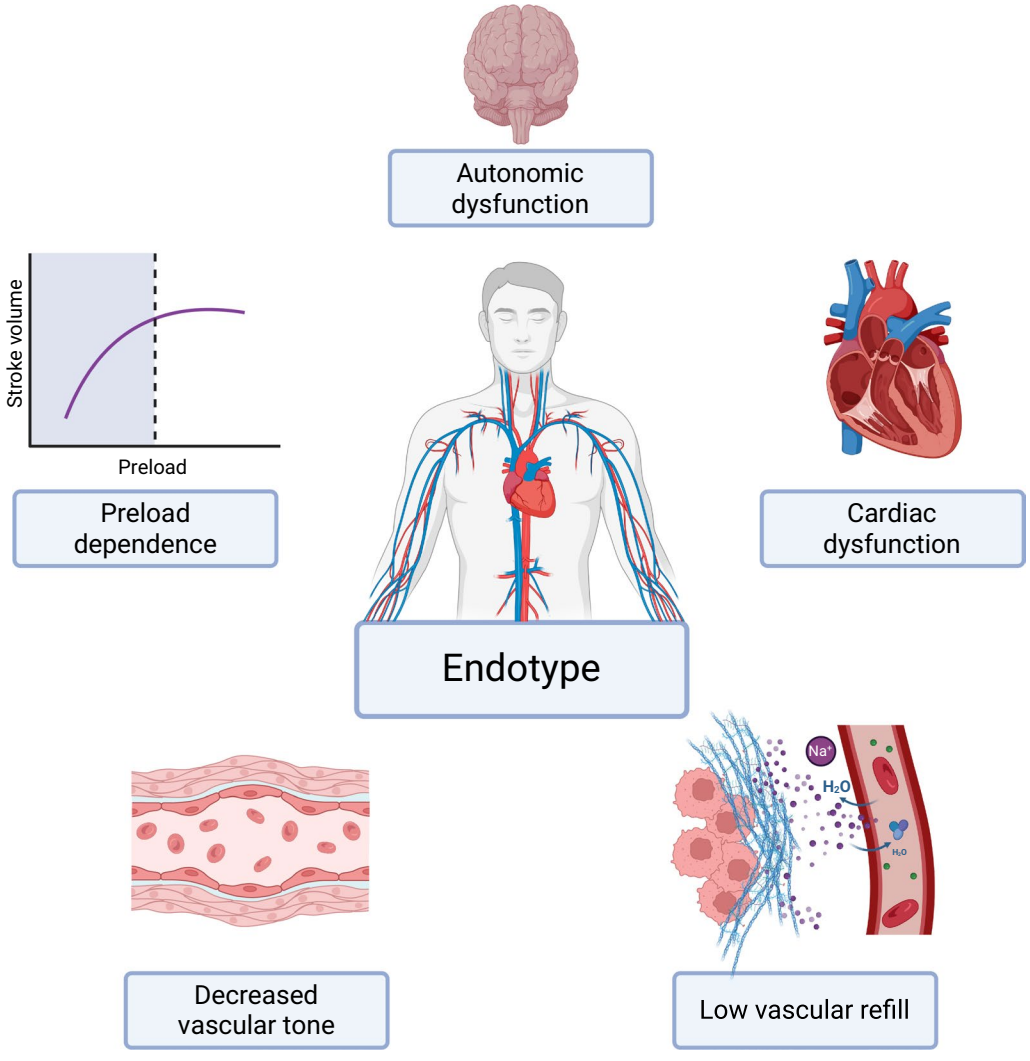

Fig. 4 Potential endotypes of UF intolerance. Five potential endotypes for developing UF intolerance are proposed: preload dependence, cardiac dysfunction, decreased vascular tone, autonomic dysfunction, and low vascular refill. Often overlapping and all occurring within the framework of poor physiological reserve. Created with BioRender.com

Preload dependence

Only a subset of IDH episodes results from preload dependence [50, 76]. Preload assessment with PLR before UF predicts intolerance [72]. Monnet et al. found that a PLR-induced increase in cardiac index of > 9% predicted HIRRT occurrence with 77% sensitivity and 96% specificity [74]. Another group showed that PLR did not accurately predict cardiac index decrease nor hypotension after a fluid removal challenge of 500 ml over one hour in patients undergoing CRRT [84], potentially because preload dependence is not the only factor contributing to UF intolerance. Bitker et al. classified hypotension episodes as related or unrelated to cardiac preload and used PLR in a protocol to guide UF [50, 72, 76]. Recently, Biscarrat et al. found that a continuous cardiac index variation ≥ 5% during a PLR may help identify patients at risk of becoming preload-dependent before UF [83].

No high-quality studies have validated alternative predictors of fluid responsiveness in this context; however, lack of responsiveness may indicate tolerance to UF and help to identify preload insufficiency as a contributor to UF intolerance, warranting further investigation of their potential role in guiding fluid removal and establishing safety limits [85].

A multimodal evaluation incorporating point-of-care ultrasound (POCUS), including LUS, inferior vena cava (IVC) ultrasound, and VExUS, may allow clinicians to estimate volume status, identify patients likely to tolerate UF and those who benefit from fluid removal [86]. Detection of "B-lines" correlates with FO [87] and decreases with UF, enabling decongestion monitoring [88, 89]. In AKI, an IVC collapsibility index > 30% predicts hypotension during slow continuous UF [90], while a low IVC collapsibility index (< 20%) suggests relative intravascular overload and a higher likelihood of tolerating UF [91]. Although each technique has limitations, combining LUS with IVC assessment can identify pre-dialysis profiles predicting IDH; patients with pulmonary congestion (B-line score ≥ 14) and hypervolemia had a lower hypotension risk [92]. An individualized, ultrasound-guided protocol integrating these tools improved the efficacy and safety of fluid removal in critically ill patients [93].

VExUS assesses systemic venous congestion resulting from elevated right atrial pressure and reduced venous compliance [94]. Prospective studies demonstrating the utility of VExUS-guided UF are lacking; however, due to the dynamic nature of these waveforms and their value in diagnosing venous congestion, repeated assessments may provide valuable information that should be explored to titrate UF. It is important to recognize that worsening degrees of venous congestion occur in patients with significant cardiovascular dysfunction and can have a narrow therapeutic index to UF (Fig. 1d).

Finally, POCUS can estimate stroke volume and CO by measuring the velocity–time integral (VTI) at the LV outflow tract. PLR-induced changes in CO, measured by various techniques including VTI, have shown high accuracy for assessing fluid responsiveness in critical care [95, 96]. However, no prospective studies have evaluated VTI specifically to guide UF.

Cardiac dysfunction

UF intolerance due to cardiogenic factors occurs both in patients with impaired baseline cardiac function and acute dysfunction. RRT can induce transient reduction of myocardial perfusion, leading to myocardial stunning and regional wall motion abnormalities [97]. This phenomenon has been reported in critically ill patients with CRRT [54] and may occur early in RRT sessions before considerable fluid removal.

Diastolic dysfunction is particularly vulnerable to reductions in filling pressure due to decreased preload during UF. Emptying the left ventricle may trigger the Bezold-Jarisch reflex [39] or, in some LV hypertrophy cases (i.e. hypertensive hypertrophy, hypertrophic cardiomyopathy), may lead to outflow tract obstruction, especially in the setting of concomitant tachycardia and low vascular resistance. In addition to LV systolic dysfunction, occult valvular abnormalities, cardiac tamponade, right ventricular dysfunction, and arrhythmias may also contribute to UF intolerance [29].

Brain natriuretic peptide and N-terminal pro B-type natriuretic peptide (NT-proBNP) are secreted by ventricular cardiomyocytes in response to myocardial stretching and volume overload [98]. Higher pre-dialysis NT-proBNP has been associated with less decline in intradialytic systolic blood pressure and a lower risk of IDH [99, 100].

Assessing LV filling pressure with POCUS may guide fluid removal. Early diastolic transmitral flow velocity (E) is determined by the pressure gradient between the LV and left atrium, while reduced early diastolic mitral annular velocity (E') indicates increased ventricular stiffness. Abrupt preload reduction from UF results in significantly decreased E-wave velocities, prolonged isovolumic relaxation time and E-wave deceleration time [101, 102]. In contrast, the E'-wave recorded at the lateral mitral annulus remains largely unchanged [102]. An E/E' ratio > 14 predicts elevated LV filling pressures, whereas lower ratios have been linked to poor tolerance of fluid removal with furosemide or UF [103, 104].

Certain therapeutic strategies to improve UF tolerance may include inotropic support, pulmonary vasodilation for right ventricular failure, prevention of ventricular emptying, control of tachycardia and loss of atrial kick in patients with diastolic dysfunction [29]. Cardiac function may also be improved by modifying the dialysis

prescription, including use of higher dialysate calcium [105], buffering severe acidosis, and application of lower dialysate temperature [28].

Decreased vascular tone

Several factors reduce vascular tone and catecholamine responsiveness, leading to IDH. The main etiology of critical illness should be considered; vasoplegia is not just ascribed to septic shock, it may also occur in hemorrhagic, cardiogenic or anaphylactic shock, and during ischemia–reperfusion, like cardiac arrest or multiple trauma. The onset of a new underlying inflammatory etiology should also be considered, as well as impaired vasopressin release and corticosteroid deficiency [29].

Hypocalcemia is common in critically ill patients, with ionized calcium < 1.02 mmol/L predicting higher mortality and HIRRT in those requiring RRT [106, 107]. It often occurs at CRRT initiation and may increase the risk of IDH through systemic vasodilation and depressed LV function. A higher dialysate calcium concentration (1.75 mmol/L) may increase extracellular calcium, arterial tone [108], SVR, and CO, and potentially improve hemodynamic tolerance [28, 29]; however, its use to prevent IDH has not been rigorously studied.

The thermal effect of RRT varies by technique. In intermittent hemodialysis, core temperature rises due to multiple factors, can cause vasodilation that may counteract the cardiovascular response to UF, and lead to hypotension [109, 110]. Cool dialysate improves hemodynamic tolerance by increasing catecholamine release, raising SVR, and centralizing blood volume via peripheral and visceral vasoconstriction [111, 112]. Convective techniques may provide better thermal stability, as large replacement fluid volumes can lower body temperature more than diffusive hemodialysis [45]. Several studies showed that lowering dialysate temperature enhanced vascular response, reduced IDH, and increased post-dialysis mean arterial pressure [113]. In critically ill patients, evidence is limited, but small randomized trials in SLED and CRRT suggest that cooling dialysate or lowering the heating device's temperature may reduce hemodynamic instability and improve UF tolerance [114–116].

Diastolic arterial pressure (DAP) is mainly determined by vascular tone. Vasodilatory shock is associated with decreased arterial tone and tachycardia, which may exert opposite effects on DAP. Therefore, DAP should be assessed alongside HR; the Diastolic shock index reflects the severity of circulatory dysfunction during vasodilatory conditions [117]. DAP is not usually considered for predicting or treating HIRRT. However, a low pre-dialysis DAP is associated with IDH in critically ill patients [118]. In septic shock, evaluating vascular tone through the severity of diastolic hypotension and diastolic shock index can be used to predict vasopressor requirements and early introduction of vasoactive agents [117, 119]. Although untested for guiding therapy, DAP and the diastolic shock index may help optimizing vasopressor use to prevent or manage UF intolerance.

Finally, improving vascular resistance adaptation to UF may enhance tolerance. Beyond temperature and calcium management, restoring vascular contractile sensitivity to catecholamines, for example, by buffering acidosis, could be beneficial. In septic shock patients on RRT, vasopressin or corticosteroids may be considered, in line with current clinical guidelines [120, 121].

Autonomic dysfunction

The autonomic nervous system plays a key role in maintaining cardiovascular homeostasis in physiological and pathological conditions, modulating neurohumoral and immune responses during systemic inflammation [122]. Autonomic dysfunction is a crucial feature in critically ill patients, impairing the required cardiovascular reflex to respond to UF.

Comorbidities such as diabetes, hypertension, heart failure, and chronic kidney disease predispose to autonomic dysfunction. Critical illness such as sepsis, trauma, or major surgery further disrupts autonomic control, with neurocritical conditions (e.g., traumatic brain injury, stroke, epilepsy, Guillain-Barré syndrome) being particularly implicated. Moreover, interventions like deep sedation and neuromuscular blockade alter chemo and baroreflexes, while autonomic dysfunction itself contributes to multiorgan failure, immune paralysis, and chronic critical illness [123–128].

Bedside autonomic nervous system monitoring remains a challenge. Tools for characterizing autonomic dysfunction include HR variability, blood pressure variability, and baroreflex analyses. HR variability measures the oscillations of the intervals between consecutive heartbeats [129], providing a noninvasive evaluation of the autonomic function and reflecting the balance between sympathetic and parasympathetic systems [130]. HR variability predicts the risk of developing sepsis, septic shock, multiorgan dysfunction, and mortality [131, 132], as well as IDH during fluid removal [133]. However, these methods have not been integrated into standard clinical practice.

The perfusion index (PI) represents the ratio between pulsatile and nonpulsatile components of the photoelectric signal originating from pulse oximetry. Peripheral hypoperfusion decreases the pulsatile component of PI, while the nonpulsatile component remains unchanged, lowering the overall PI value [134, 135]. The PI is a simple, inexpensive, and noninvasive measure of peripheral microcirculatory perfusion [136] and has high sensitivity to changes in sympathetic stimulation and different body positions [137, 138]. The hemodynamic responses of the

PI values to changes in body position have been used as a monitoring tool in fluid therapy. During PLR, an increase in PI by 9% accurately detects a positive response of the PLR test [139]. Klijn et al. evaluated whether the PI before and during UF in CRRT could predict hypotension due to impaired vasoconstriction in critically ill patients. Findings suggest that hypotension appeared to result from inadequate vasoconstriction during fluid removal. In patients without hypotension, PI decreased while SVR increased, implying that peripheral vasoconstriction reduces PI and preserves blood pressure. In contrast, hypotensive patients tend to have higher baseline SVR and thus less capacity for further vasoconstriction. Hence, the primary difference at baseline was a lower PI in hypotensive patients, suggesting that PI reflects basal vasomotor tone. A baseline PI ≤ 0.82 may predict hypotension during UF with 70% sensitivity and 92% specificity [140]. Similarly, low PI and low HR variability have been identified as predictors of IDH during intermittent hemodialysis [141].

Low vascular refill

The vascular refill rate ranges between 2 to 6 ml/kg/h during intermittent hemodialysis but may exceed 10 ml/kg/h at high UF rates [142, 143]. The most challenging factor to estimate is the vascular refill rate, especially for critically ill patients with endothelial glycocalyx disruption, impaired lymphatic function, and interstitial structural modification. Using transpulmonary thermodilution device, a higher pulmonary vascular permeability index (PVPI) reflected increased capillary permeability within the pulmonary vasculature and correlated with impaired plasma refilling [28, 76]. A PVPI ≥ 1.6 at intermittent hemodialysis onset predicts hypotension associated with preload dependence [76]. A potential strategy to indirectly assess the balance between vascular refill and UF rate is continuous hematocrit monitoring to estimate relative blood volume. Recent data in critically ill patients undergoing CRRT confirm its feasibility and show that greater relative blood volume declines occur with higher UF rates, suggesting potential utility for optimizing UF and preventing intravascular volume depletion [144].

Despite frequent clinical use, evidence supporting albumin administration to prevent or treat UF intolerance during RRT remains weak. Hypoalbuminemia is common in critically ill patients and has been associated with IDH [145–147]; however, translating this association into therapeutic benefit has not been demonstrated. A Cochrane review identified only a single small crossover trial comparing 5% albumin with saline, which showed no difference in UF or hemodynamic outcomes [148–151]. Subsequent studies evaluating hyperoncotic albumin administration have reported variable effects on short-term hemodynamic parameters, but these studies are small, heterogeneous, and largely limited to physiologic or surrogate endpoints, without evidence of sustained UF improvement or patient-centered benefit [152, 153]. Importantly, adequately powered randomized trials evaluating albumin during CRRT to prevent or treat hemodynamic instability are lacking.

Although autopsy studies have not demonstrated renal albumin accumulation after exposure to hyperoncotic albumin [154], observational studies in cardiac surgery populations have reported a dose-dependent association between hyperoncotic albumin and AKI [155]. Randomized data are inconsistent: while some trials and meta-analyses suggest neutral renal effects [156–158], a recent randomized trial in cardiac surgery patients at high risk for AKI demonstrated an increased incidence of AKI with 20% albumin administration [159]. Collectively, these findings argue against a clear renal safety advantage and underscore potential harm in susceptible populations. Given weak and heterogeneous evidence, guidelines do not recommend albumin to prevent or treat IDH, or to improve UF [160]. Future studies are needed to clarify whether albumin administration, in individualized physiological endotypes (e.g., low vascular refill, hypoalbuminemia), could improve UF tolerance.

During hemodialysis, rapid serum sodium clearance reduces plasma osmolality, thereby promoting the shift of free water from intravascular to extravascular compartments. This results in decreased effective blood volume and reduced vascular refilling, leading to HIRRT when compensatory mechanisms or UF rates are inadequate [28]. Indeed, decreased plasma osmolality during intermittent hemodialysis is a risk factor for hemodynamic instability [45]. During CRRT, plasma osmolality changes should be slower and less likely to provoke HIRRT. High sodium dialysate concentration (> 145 mmol/L) is one component of a regimen that limits osmotic shift and promotes hemodynamic stability [161].

Finally, vasopressor administration improves adaptation of peripheral vascular resistance to volume depletion and, according to Starling forces, precapillary vasoconstriction could decrease intravascular hydrostatic pressure and facilitate vascular refilling [161].

Proposed strategy: a step towards personalized ultrafiltration

This pathophysiological approach seeks to deliver personalized UF (Fig. 5) and prevent, rather than react to, adverse events. UF intolerance could be predicted by emulating fluid removal with dynamic tests (e.g., passive leg lowering, UF challenge). If intolerance occurs, the predominant clinical endotype should be identified (Fig. 6) and optimized before therapy, such as correction of preload dependence, cardiac dysfunction, decreased vascular tone, autonomic dysfunction, or low vascular

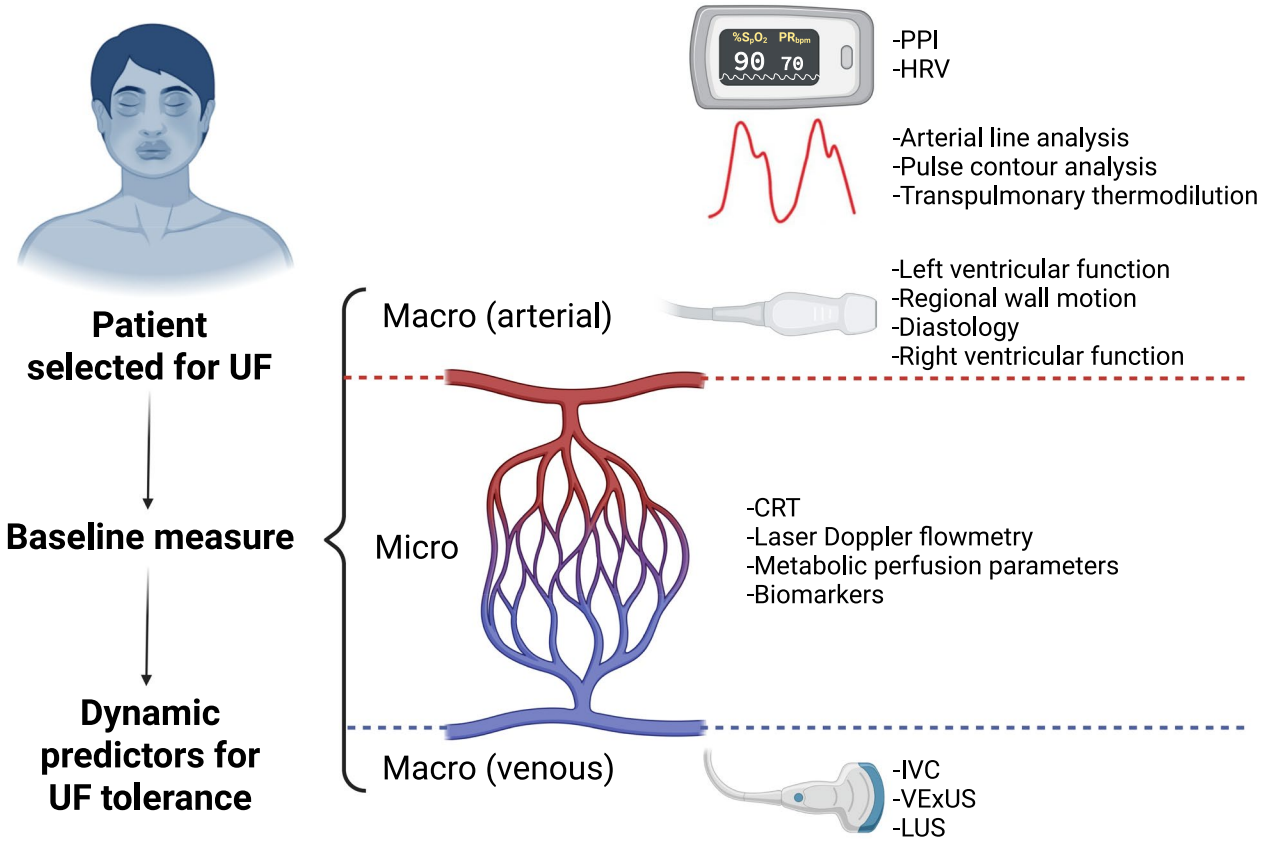

Fig. 5 Proposed strategy: First step (Baseline measures). In patients selected for UF, several baseline variables should be measured: on the arterial side variables like SAP, DAP, PP, PPV, and data derived from pulse contour analysis and transpulmonary thermodilution if accessible. Focused cardiac ultrasound evaluating left systolic and diastolic ventricular function, regional wall motion, and right ventricular function. On the venous side, IVC, VExUS, and LUS would be measured. Perfusion variables are fundamental to defining UF intolerance, CRT, skin blood flow measured by laser Doppler flowmetry, and metabolic perfusion parameters. While not formally validated for HIRRT prediction, biomarkers reflecting volume status (N-terminal pro-B-type natriuretic peptide) and oncotic pressure (albumin levels) may nevertheless contribute complementary information when assessing the risk of UF intolerance. SAP: systolic arterial pressure, DAP: diastolic arterial pressure, PP: pulse pressure, PPV: pulse pressure variation, PPI: peripheral perfusion index, HRV: heart rate variability, CRT: capillary refill time, IVC: inferior vena cava, VExUS: venous excess ultrasound, LUS: lung ultrasound. Created with BioRender.com

refill (Fig. 7). Given that multiple overlapping endotypes may coexist, tailoring UF to address them should improve tolerance. Continuous reassessment during each RRT session is essential, as tolerance can shift over time. This strategy remains theoretical and requires validation in future studies.

Conclusions

Ultrafiltration intolerance in critically ill patients is a multifactorial phenomenon that cannot be solely attributed to intravascular volume depletion. Its prevention and management require incorporation of pathophysiological principles into individualized treatment strategies. Dynamic assessments, ultrasound-based monitoring, and evaluation of perfusion metrics may help to identify patient-specific endotypes and guide tailored UF prescriptions. The proposed framework emphasizes proactive identification and correction of reversible mechanisms before and during RRT, aiming to improve hemodynamic tolerance and reduce complications. Future studies should validate these concepts to establish evidence-based protocols for personalized UF in critical care.

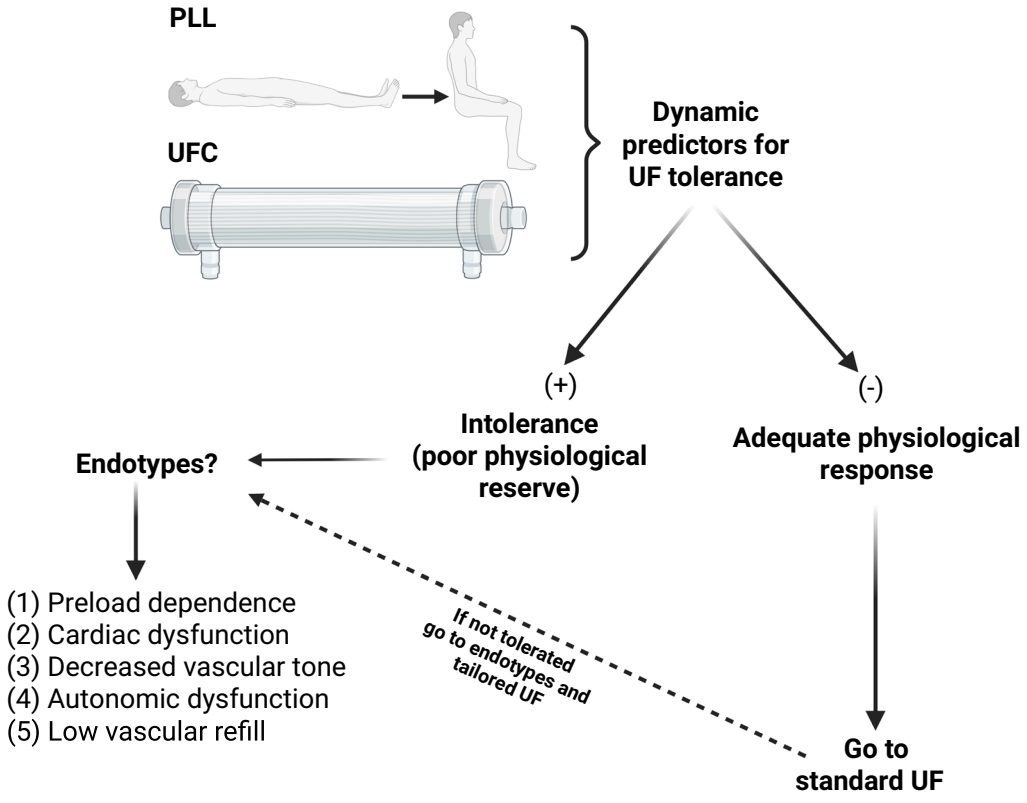

Fig. 6 Proposed strategy: Second step (Predict intolerance). In order to predict UF tolerance, PLL and MUC would be done. After the test, a new measure (the same as baseline variables) will determine if patients develop intolerance (hemodynamic instability and tissue hypoperfusion). In case poor physiological reserve is unmasked, endotypes should be sought. PLL: passive leg lowering, UFC: ultrafiltration challenge. Created with BioRender.com

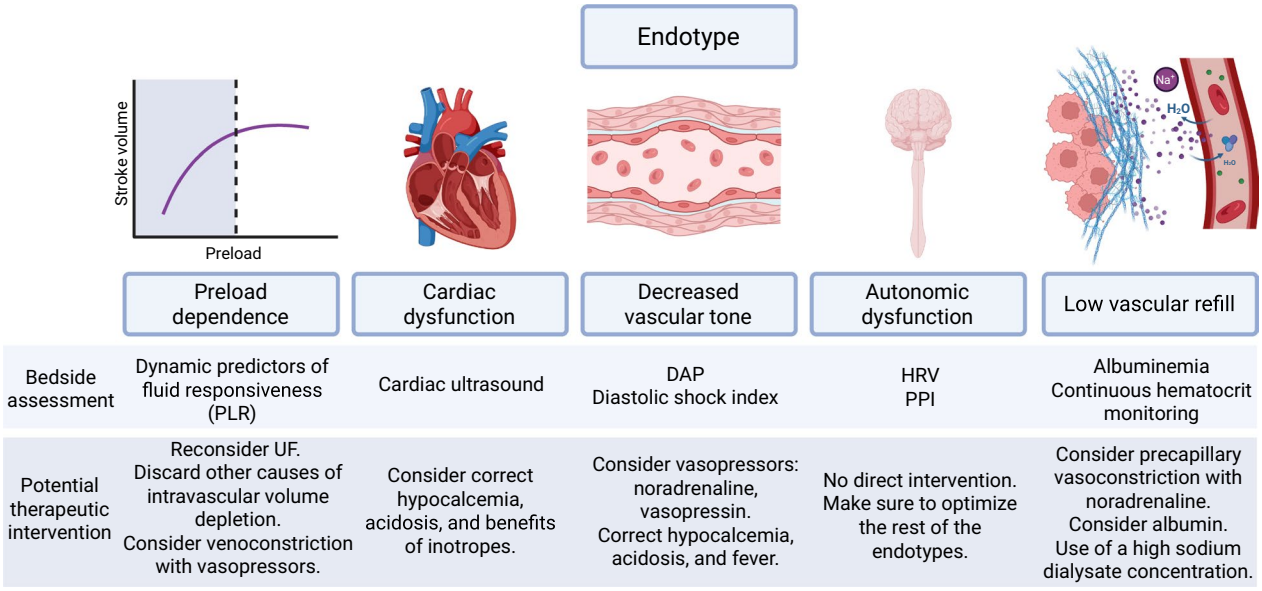

Fig. 7 Proposed strategy: Third step (Search endotypes). Once intolerance has been proven, bedside assessments should guide physicians to different endotypes: preload dependence, cardiac dysfunction, decreased vascular tone, autonomic dysfunction, and low vascular refill. These endotypes often overlap, and therapeutic interventions may improve more than one mechanism. For example, in a patient with pancreatitis underlying septic shock on CRRT, a positive PLR test may predict preload dependence. A potential intervention that could enhance UF tolerance could be the induction of venoconstriction with noradrenaline before UF. Additionally, noradrenaline will produce precapillary vasoconstriction, improving vascular refill and vascular tone. However, in the context of preload dependence, it's imperative to discard alternative etiologies of intravascular volume depletion (i.e. gastrointestinal bleeding) and, in some cases, reconsider the timing of UF. PLR: passive leg raising, DAP: diastolic arterial pressure, HRV: heart rate variability, PPI: peripheral perfusion index. Created with BioRender.com

Abbreviations

FO	Fluid overload
AKI	Acute kidney injury
UF	Ultrafiltration
RRT	Renal replacement therapy
UF_{NET}	Net ultrafiltration
IDH	Intradialytic hypotension
HIRRT	Hemodynamic instability related to renal replacement therapy
CRRT	Continuous renal replacement therapy
CO	Cardiac output
HR	Heart rate
LV	Left ventricular
SVR	Systemic vascular resistance
SLED	Sustained low-efficiency dialysis
LUS	Lung ultrasound
VExUS	Venous excess ultrasound
CRT	Capillary refill time
PLR	Passive leg raising
POCUS	Point-of-care ultrasound
IVC	Inferior vena cava
VTI	Velocity–time integral
NT-proBNP	N-terminal pro B-type natriuretic peptide
E	Early diastolic transmitral flow velocity
E′	Early diastolic mitral annular velocity
DAP	Diastolic arterial pressure
PI	Perfusion index
PVPI	Pulmonary vascular permeability index

Acknowledgements
None

Author contributions
Conceptualization and designed the review: PM and EK. Literature search: PM and EK. Writing-Original draft preparation: PM and EK. Writing-Review and editing: All authors. Approved of final manuscript: All authors.

Funding
This study has been funded by FONDECYT Grant Nº 1230475 (EK).

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent of publication
Not applicable.

Competing interests
GRG has received funding for lectures from B. Braun, Vantive, Fresenius Medical Care, and Jafron. AW has received funding for lectures from Mindray, GE and Getinge. MO has received research funding from Biomerieux and Baxter (paid to the institution).

Author details
[1]Intensive Care Unit, Hospital Santiago Oriente Dr. Luis Tisné Brousse, Santiago, Chile
[2]Departamento de Medicina Intensiva, Facultad de Medicina, Pontificia Universidad Católica de Chile, Avenida Diagonal Paraguay 362, Santiago, Chile
[3]Nephrology Service, Hospital Las Higueras, Talcahuano, Chile
[4]Department of Critical Care, King's College Hospital NHS Foundation Trust, London, UK
[5]Escuela de Medicina y Ciencias de la Salud, Tecnológico de Monterrey, Mexico City, Mexico
[6]Departamento de Nefrología y Metabolismo Mineral, Instituto Nacional de Ciencias Médicas y Nutrición Salvador Zubirán, Mexico City, Mexico
[7]Department of Critical Care, Guy's & St Thomas' NHS Foundation Trust, London, UK

[8]SENTINET: Surveillance, Epidemiology, and New Technologies for Infectious Emerging Threats, Santiago, Chile

Received: 13 November 2025 / Accepted: 6 January 2026
Published online: 24 January 2026

References

1. Balakumar V, Murugan R, Sileanu FE, Palevsky P, Clermont G, Kellum JA. Both positive and negative fluid balance may be associated with reduced long-term survival in the critically ill. Crit Care Med. 2017;45(8):e749–57.
2. Garzotto F, Ostermann M, Martín-Langerwerf D, Sánchez-Sánchez M, Teng J, Robert R, et al. The dose response multicentre investigation on fluid assessment (DoReMIFA) in critically ill patients. Crit Care. 2016;20(1):196.
3. Payen D, de Pont AC, Sakr Y, Spies C, Reinhart K, Vincent JL. A positive fluid balance is associated with a worse outcome in patients with acute renal failure. Crit Care. 2008;12(3):R74.
4. Salahuddin N, Sammani M, Hamdan A, Joseph M, Al-Nemary Y, Alquaiz R, et al. Fluid overload is an independent risk factor for acute kidney injury in critically ill patients: results of a cohort study. BMC Nephrol. 2017;18(1):45.
5. Heung M, Wolfgram DF, Kommareddi M, Hu Y, Song PX, Ojo AO. Fluid overload at initiation of renal replacement therapy is associated with lack of renal recovery in patients with acute kidney injury. Nephrol Dial Transplant. 2012;27(3):956–61.
6. Koc V, Delmas Benito L, de With E, Boerma EC. The effect of fluid overload on attributable morbidity after cardiac surgery: a retrospective study. Crit Care Res Pract. 2020;2020:1–7.
7. Vaara ST, Korhonen AM, Kaukonen KM, Nisula S, Inkinen O, Hoppu S, et al. Fluid overload is associated with an increased risk for 90-day mortality in critically ill patients with renal replacement therapy: data from the prospective FINNAKI study. Crit Care. 2012;16(5):R197.
8. Mitchell KH, Carlbom D, Caldwell E, Leary PJ, Himmelfarb J, Hough CL. Volume overload: prevalence, risk factors, and functional outcome in survivors of septic shock. Ann Am Thorac Soc. 2015;12(12):1837–44.
9. Woodward CW, Lambert J, Ortiz-Soriano V, Li Y, Ruiz-Conejo M, Bissell BD, et al. Fluid overload associates with major adverse kidney events in critically ill patients with acute kidney injury requiring continuous renal replacement therapy. Crit Care Med. 2019;47(9):e753–60.
10. Murugan R, Bellomo R, Palevsky PM, Kellum JA. Ultrafiltration in critically ill patients treated with kidney replacement therapy. Nat Rev Nephrol. 2021;17(4):262–76.
11. Reis T, Ronco C, Soranno DE, Clark W, de Rosa S, Forni LG, et al. Standardization of nomenclature for the mechanisms and materials utilized for extracorporeal blood purification. Blood Purif. 2024;53(5):329–42.
12. RENAL Replacement Therapy Study Investigators, Bellomo R, Cass A, Cole L, Finfer S, Gallagher M, et al. An observational study fluid balance and patient outcomes in the Randomized Evaluation of Normal vs. Augmented Level of Replacement Therapy trial. Crit Care Med. 2012;40(6):1753–60.
13. Bouchard J, Soroko SB, Chertow GM, Himmelfarb J, Ikizler TA, Paganini EP, et al. Fluid accumulation, survival and recovery of kidney function in critically ill patients with acute kidney injury. Kidney Int. 2009;76(4):422–7.
14. RENAL Replacement Therapy Study Investigators, Bellomo R, Cass A, Cole L, Finfer S, Gallagher M, et al. Intensity of continuous renal-replacement therapy in critically ill patients. NEJM. 2009;361(17):1627–38.
15. VANISH Acute Renal Failure Trial Network, Palevsky PM, Zhang JH, O'Connor TZ, Chertow GM, Crowley ST, et al. Intensity of renal support in critically ill patients with acute kidney injury. NEJM. 2008;359(1):7–20.
16. Murugan R, Balakumar V, Kerti SJ, Priyanka P, Chang CCH, Clermont G, et al. Net ultrafiltration intensity and mortality in critically ill patients with fluid overload. Crit Care. 2018;22(1):223.
17. Pirkle JL, Comeau ME, Langefeld CD, Russell GB, Balderston SS, Freedman BI, et al. Effects of weight-based ultrafiltration rate limits on intradialytic hypotension in hemodialysis. Hemodial Int. 2018;22(2):270–8.
18. Neri M, Villa G, Garzotto F, Bagshaw S, Bellomo R, Cerda J, et al. Nomenclature for renal replacement therapy in acute kidney injury: basic principles. Crit Care. 2016;20(1):318.
19. Murugan R, Kerti SJ, Chang CCH, Gallagher M, Clermont G, Palevsky PM, et al. Association of net ultrafiltration rate with mortality among critically ill adults with acute kidney injury receiving continuous venovenous hemodiafiltration. JAMA Netw Open. 2019;2(6):e195418.
20. Neyra JA, Lambert J, Ortiz-Soriano V, Cleland D, Colquitt J, Adams P, et al. Assessment of prescribed vs. achieved fluid balance during continuous renal replacement therapy and mortality outcome. PLoS One. 2022;17(8):e0272913.
21. Akhoundi A, Singh B, Vela M, Chaudhary S, Monaghan M, Wilson GA, et al. Incidence of adverse events during continuous renal replacement therapy. Blood Purif. 2015;39(4):333–9.
22. Shawwa K, Kompotiatis P, Jentzer JC, Wiley BM, Williams AW, Dillon JJ, et al. Hypotension within one-hour from starting CRRT is associated with in-hospital mortality. J Crit Care. 2019;54:7–13.
23. Uchino S, Bellomo R, Morimatsu H, Morgera S, Schetz M, Tan I, et al. Continuous renal replacement therapy: a worldwide practice survey. Intensive Care Med. 2007;33(9):1563–70.
24. Vinsonneau C, Camus C, Combes A, de Costa Beauregard MA, Klouche K, Boulain T, et al. Continuous venovenous haemodiafiltration versus intermittent haemodialysis for acute renal failure in patients with multiple-organ dysfunction syndrome: a multicentre randomised trial. Lancet. 2006;368(9533):379–85.
25. Lima EQ, Silva RG, Donadi ELS, Fernandes AB, Zanon JR, Pinto KRD, et al. Prevention of intradialytic hypotension in patients with acute kidney injury submitted to sustained low-efficiency dialysis. Ren Fail. 2012;34(10):1238–43.
26. Ballarin Albino B, Balbi AL, Ponce D. Dialysis complications in AKI patients treated with extended daily dialysis: is the duration of therapy important? BioMed Res Int. 2014;2014:1–9.
27. Tehranian S, Shawwa K, Kashani KB. Net ultrafiltration rate and its impact on mortality in patients with acute kidney injury receiving continuous renal replacement therapy. Clin Kidney J. 2021;14(2):564–9.
28. Douvris A, Zeid K, Hiremath S, Bagshaw SM, Wald R, Beaubien-Souligny W, et al. Mechanisms for hemodynamic instability related to renal replacement therapy: a narrative review. Intensive Care Med. 2019;45(10):1333–46.
29. Doshi M, Murray PT. Approach to intradialytic hypotension in intensive care unit patients with acute renal failure. Artif Organs. 2003;27(9):772–80.
30. Daugirdas JT. Pathophysiology of dialysis hypotension: an update. Am J Kidney Dis. 2001;38(4):S11–7.
31. Daugirdas JT. Dialysis hypotension: a hemodynamic analysis. Kidney Int. 1991;39(2):233–46.
32. Koomans HA, Geers AB, Dorhout Mees EJ. Plasma volume recovery after ultrafiltration in patients with chronic renal failure. Kidney Int. 1984;26(6):848–54.
33. Sander-Jensen K, Mehlsen J, Stadeager C, Christensen NJ, Fahrenkrug J, Schwartz TW, et al. Increase in vagal activity during hypotensive lower-body negative pressure in humans. Am J Physiol. 1988;255(1):R149–56.
34. Ushioda E, Nuwayhid B, Kleinman G, Tabsh K, Brinkman CR, Assali NS. The contribution of the β-adrenergic system to the cardiovascular response to hypovolemia. Am J Obstet Gynecol. 1983;147(4):423–9.
35. Shen YT, Knight DR, Thomas JX, Vatner SF. Relative roles of cardiac receptors and arterial baroreceptors during hemorrhage in conscious dogs. Circ Res. 1990;66(2):397–405.
36. Dasselaar JJ, Slart RHJA, Knip M, Pruim J, Tio RA, McIntyre CW, et al. Haemodialysis is associated with a pronounced fall in myocardial perfusion. Nephrol Dial Transpl. 2008;24(2):604–10.
37. Kotecha T, Martinez-Naharro A, Yoowannakul S, Lambe T, Rezk T, Knight DS, et al. Acute changes in cardiac structural and tissue characterisation parameters following haemodialysis measured using cardiovascular magnetic resonance. Sci Rep. 2019;9(1):1388.
38. Burton JO, Jefferies HJ, Selby NM, McIntyre CW. Hemodialysis-induced cardiac injury. Clin J Am Soc Nephrol. 2009;4(5):914–20.
39. Converse RL, Jacobsen TN, Jost CM, Toto RD, Grayburn PA, Obregon TM, et al. Paradoxical withdrawal of reflex vasoconstriction as a cause of hemodialysis-induced hypotension. J Clin Invest. 1992;90(5):1657–65.
40. Escoli R, Carvalho MJ, Cabrita A, Rodrigues A. Diastolic dysfunction, an underestimated new challenge in dialysis. Ther Apher Dial. 2019;23(2):108–17.
41. Rolando G, Espinoza EDV, Avid E, Welsh S, del Pozo J, Vazquez AR, et al. Prognostic value of ventricular diastolic dysfunction in patients with severe sepsis and septic shock. Rev Bras Ter Intensiva. 2015;27(4):333–9.
42. Landesberg G, Gilon D, Meroz Y, Georgieva M, Levin PD, Goodman S, et al. Diastolic dysfunction and mortality in severe sepsis and septic shock. Eur Heart J. 2012;33(7):895–903.
43. Rothe CF. Reflex control of veins and vascular capacitance. Physiol Rev. 1983;63(4):1281–342.
44. Daugirdas JT. Intradialytic hypotension and splanchnic shifting: integrating an overlooked mechanism with the detection of ischemia-related signals during hemodialysis. Semin Dial. 2019;32(3):243–7.

45. Schortgen F. Hypotension during intermittent hemodialysis: new insights into an old problem. Intensive Care Med. 2003;29(10):1645–9.
46. Bemelmans RHH, Boerma EC, Barendregt J, Ince C, Rommes JH, Spronk PE. Changes in the volume status of haemodialysis patients are reflected in sublingual microvascular perfusion. Nephrol Dial Transplant. 2009;24(11):3487–92.
47. Veenstra G, Pranskunas A, Skarupskiene I, Pilvinis V, Hemmelder MH, Ince C, et al. Ultrafiltration rate is an important determinant of microcirculatory alterations during chronic renal replacement therapy. BMC Nephrol. 2017;18(1):71.
48. Silversides JA, Pinto R, Kuint R, Wald R, Hladunewich MA, Lapinsky SE, et al. Fluid balance, intradialytic hypotension, and outcomes in critically ill patients undergoing renal replacement therapy: a cohort study. Crit Care. 2014;18(6):624.
49. Douvris A, Malhi G, Hiremath S, McIntyre L, Silver SA, Bagshaw SM, et al. Interventions to prevent hemodynamic instability during renal replacement therapy in critically ill patients: a systematic review. Crit Care. 2018;22(1):41.
50. Chazot G, Bitker L, Mezidi M, Chebib N, Chabert P, Chauvelot L, et al. Prevalence and risk factors of hemodynamic instability associated with preload-dependence during continuous renal replacement therapy in a prospective observational cohort of critically ill patients. Ann Intensive Care. 2021;11(1):95.
51. Polinder-Bos HA, García DV, Kuipers J, Elting JWJ, Aries MJH, Krijnen WP, et al. Hemodialysis induces an acute decline in cerebral blood flow in elderly patients. J Am Soc Nephrol. 2018;29(4):1317–25.
52. Findlay MD, Dawson J, Dickie DA, Forbes KP, McGlynn D, Quinn T, et al. Investigating the relationship between cerebral blood flow and cognitive function in hemodialysis patients. J Am Soc Nephrol. 2019;30(1):147–58.
53. Burton JO, Korsheed S, Grundy BJ, McIntyre CW. Hemodialysis-induced left ventricular dysfunction is associated with an increase in ventricular arrhythmias. Ren Fail. 2008;30(7):701–9.
54. Slessarev M, Salerno F, Ball IM, McIntyre CW. Continuous renal replacement therapy is associated with acute cardiac stunning in critically ill patients. Hemodial Int. 2019;23(3):325–32.
55. Ribitsch W, Schneditz D, Franssen CFM, Schilcher G, Stadlbauer V, Horina JH, et al. Increased hepato-splanchnic vasoconstriction in diabetics during regular hemodialysis. PLoS One. 2015;10(12):e0145411.
56. Conger JD. Does hemodialysis delay recovery from acute renal failure? Semin Dial. 1990;3(3):146–8.
57. Augustine JJ, Sandy D, Seifert TH, Paganini EP. A randomized controlled trial comparing intermittent with continuous dialysis in patients with ARF. Am J Kidney Dis. 2004;44(6):1000–7.
58. Gouin M, Joyal R, Lamothe M, Luo YH, Fan XY, Huard K, et al. Achievement of fluid removal targets during intermittent renal replacement therapy in the intensive care unit. Clin Kidney J. 2024;17(9):sfae257.
59. O'Connor ME, Jones SL, Glassford NJ, Bellomo R, Prowle JR. Defining fluid removal in the intensive care unit: a national and international survey of critical care practice. J Intensive Care Soc. 2017;18(4):282–8.
60. Ledoux-Hutchinson L, Wald R, Malbrain MLNG, Carrier FM, Bagshaw SM, Bellomo R, et al. Fluid management for critically ill patients with acute kidney injury receiving kidney replacement therapy. Clin J Am Soc Nephrol. 2023;18(6):705–15.
61. Wiener RS, Welch HG. Trends in the use of the pulmonary artery catheter in the United States, 1993–2004. JAMA. 2007;298(4):423–9.
62. Gershengorn HB, Wunsch H. Understanding changes in established practice. Crit Care Med. 2013;41(12):2667–76.
63. Coverdale G, Patteril M. Do pulmonary artery catheters have a role in the 21st century intensive care unit? Br J Anaesth. 2022;129(1):3–7.
64. Villavicencio C, Leache J, Marin J, Oliva I, Rodriguez A, Bodí M, et al. Basic critical care echocardiography training of intensivists allows reproducible and reliable measurements of cardiac output. Ultrasound J. 2019;11(1):5.
65. Bergamaschi V, Vignazia GL, Messina A, Colombo D, Cammarota G, Corte F, et al. Transthoracic echocardiographic assessment of cardiac output in mechanically ventilated critically ill patients by intensive care unit physicians. Brazilian Journal of Anesthesiology (English Edition). 2019;69(1):20–6.
66. Mercado P, Maizel J, Beyls C, Titeca-Beauport D, Joris M, Kontar L, et al. Transthoracic echocardiography: an accurate and precise method for estimating cardiac output in the critically ill patient. Crit Care. 2017;21(1):136.
67. De Laet I, Deeren D, Schoonheydt K, van Regenmortel N, Dits H, Malbrain ML. Renal replacement therapy with net fluid removal lowers intra-abdominal pressure and volumetric indices in critically ill patients. Ann Intensive Care. 2012;2(S1):S20.
68. Huber W, Fuchs S, Minning A, Küchle C, Braun M, Beitz A, et al. Transpulmonary thermodilution (TPTD) before, during and after sustained low efficiency dialysis (SLED). A prospective study on feasibility of TPTD and prediction of successful fluid removal. PLoS One. 2016;11(4):e0153430.
69. Murugan R, Kashani K, Palevsky PM. Precision net ultrafiltration dosing in continuous kidney replacement therapy: a practical approach. Intensive Care Med Exp. 2023;11(1):83.
70. Ostermann M, Joannidis M. Acute kidney injury 2016: diagnosis and diagnostic workup. Crit Care. 2016;20(1):299.
71. Bigé N, Lavillegrand JR, Dang J, Attias P, Deryckere S, Joffre J, et al. Bedside prediction of intradialytic hemodynamic instability in critically ill patients: the SOCRATE study. Ann Intensive Care. 2020;10(1):47.
72. Bitker L, Dupuis C, Pradat P, Deniel G, Klouche K, Mezidi M, et al. Fluid balance neutralization secured by hemodynamic monitoring versus protocolized standard of care in patients with acute circulatory failure requiring continuous renal replacement therapy: results of the GO NEUTRAL randomized controlled trial. Intensive Care Med. 2024;50(12):2061–72.
73. Mongkolpun W, Bakos P, Vincent JL, Creteur J. Monitoring skin blood flow to rapidly identify alterations in tissue perfusion during fluid removal using continuous veno-venous hemofiltration in patients with circulatory shock. Ann Intensive Care. 2021;11(1):59.
74. Monnet X, Cipriani F, Camous L, Sentenac P, Dres M, Krastinova E, et al. The passive leg raising test to guide fluid removal in critically ill patients. Ann Intensive Care. 2016;6(1):46.
75. Bitker L, Bayle F, Yonis H, Gobert F, Leray V, Taponnier R, et al. Prevalence and risk factors of hypotension associated with preload-dependence during intermittent hemodialysis in critically ill patients. Crit Care. 2016;20(1):44.
76. Ramírez-Guerrero G, Ronco C. Ultrafiltration tolerance: a phenotype that we need to recognize. Blood Purif. 2024;53(7):541–7.
77. Kattan E, Castro R, Miralles-Aguiar F, Hernández G, Rola P. The emerging concept of fluid tolerance: a position paper. J Crit Care. 2022;71:154070.
78. Buhre W, Weyland A, Buhre K, Kazmaier S, Mursch K, Schmidt M, et al. Effects of the sitting position on the distribution of blood volume in patients undergoing neurosurgical procedures. Br J Anaesth. 2000;84(3):354–7.
79. Bouchant L, Godet T, Arpajou G, Aupetitgendre L, Cayot S, Guerin R, et al. Physiological effects and safety of bed verticalization in patients with acute respiratory distress syndrome. Crit Care. 2024;28(1):262.
80. Monnet X, Rienzo M, Osman D, Anguel N, Richard C, Pinsky MR, et al. Passive leg raising predicts fluid responsiveness in the critically ill. Crit Care Med. 2006;34(5):1402–7.
81. Jabot J, Teboul JL, Richard C, Monnet X. Passive leg raising for predicting fluid responsiveness: importance of the postural change. Intensive Care Med. 2009;35(1):85–90.
82. Huang D, Ma H, Ma J, Hong L, Lian X, Wu Y, et al. A novel supplemental maneuver to predict fluid responsiveness in critically ill patients: blood pump-out test performed before renal replacement therapy. Ann Transl Med. 2020;8(12):786–786.
83. Biscarrat C, Deniel G, Chivot M, Yonis H, Chauvelot L, Mezidi M, et al. Diagnostic performance of a 250-ml net ultrafiltration challenge to identify risk of preload-dependence in critically ill patients undergoing continuous renal replacement therapy: a randomized, cross-over trial. Crit Care. 2025;29(1):446.
84. Jacquet-Lagrèze M, Ruste M, Fornier W, Jacquemet PL, Schweizer R, Fellahi JL. Refilling and preload dependence failed to predict cardiac index decrease during fluid removal with continuous renal replacement therapy. J Nephrol. 2022;36(1):187–97.
85. Castro R, Born P, Roessler E, Labra C, McNab P, Bravo S, et al. Preload responsiveness–guided fluid removal in mechanically ventilated patients with fluid overload: a comprehensive clinical–physiological study. J Crit Care. 2024;84:154901.
86. Rola P, Miralles-Aguiar F, Argaiz E, Beaubien-Souligny W, Haycock K, Karimov T, et al. Clinical applications of the venous excess ultrasound (VExUS) score: conceptual review and case series. Ultrasound J. 2021;13(1):32.
87. Ciumanghel A, Siriopol I, Blaj M, Siriopol D, Gavrilovici C, Covic A. B-lines score on lung ultrasound as a direct measure of respiratory dysfunction in ICU patients with acute kidney injury. Int Urol Nephrol. 2018;50(1):113–9.
88. Noble VE, Murray AF, Capp R, Sylvia-Reardon MH, Steele DJR, Liteplo A. Ultrasound assessment for extravascular lung water in patients undergoing hemodialysis. Chest. 2009;135(6):1433–9.
89. Beaubien-Souligny W, Rhéaume M, Blondin MC, El-Barnachawy S, Fortier A, Éthier J, et al. A simplified approach to extravascular lung water assessment using point-of-care ultrasound in patients with end-stage chronic renal failure undergoing hemodialysis. Blood Purif. 2018;45(1–3):79–87.

90. Guiotto G, Masarone M, Paladino F, Ruggiero E, Scott S, Verde S, et al. Inferior vena cava collapsibility to guide fluid removal in slow continuous ultrafiltration: a pilot study. Intensive Care Med. 2010;36(4):692–6.
91. Kaptein M, Kaptein J, Oo Z, Kaptein E. Relationship of inferior vena cava collapsibility to ultrafiltration volume achieved in critically ill hemodialysis patients. Int J Nephrol Renovasc Dis. 2018;11:195–209.
92. da Hora Passos R, Caldas J, Ramos JGR, dos Santos Galvão De Melo EB, Ribeiro MPD, Alves MFC, et al. Ultrasound-based clinical profiles for predicting the risk of intradialytic hypotension in critically ill patients on intermittent dialysis: a prospective observational study. Crit Care. 2019;23(1):389.
93. Wang L, Qiu C, Guan X, Chen M, Chen J, Si X, et al. Fluid removal with ultrasound guided protocol improves the efficacy and safety of dehydration in post-resuscitated critically ill patients: a quasi-experimental, before and after study. Shock. 2018;50(4):401–7.
94. Beaubien-Souligny W, Rola P, Haycock K, Bouchard J, Lamarche Y, Spiegel R, et al. Quantifying systemic congestion with point-of-care ultrasound: development of the venous excess ultrasound grading system. Ultrasound J. 2020;12(1):16.
95. Cherpanath TG, Hirsch A, Geerts BF, Lagrand WK, Leeflang MM, Schultz MJ, et al. Predicting fluid responsiveness by passive leg raising. Crit Care Med. 2016;44(5):981–91.
96. Monnet X, Marik P, Teboul JL. Passive leg raising for predicting fluid responsiveness: a systematic review and meta-analysis. Intensive Care Med. 2016;42(12):1935–47.
97. McIntyre CW, Burton JO, Selby NM, Leccisotti L, Korsheed S, Baker CSR, et al. Hemodialysis-induced cardiac dysfunction is associated with an acute reduction in global and segmental myocardial blood flow. Clin J Am Soc Nephrol. 2008;3(1):19–26.
98. Azzazy HME, Christenson RH. B-type natriuretic peptide: physiologic role and assay characteristics. Heart Fail Rev. 2003;8(4):315–20.
99. Chou YH, Chen YF, Pan SY, Huang TM, Yang FJ, Shen WC, et al. The role of brain natriuretic peptide in predicting renal outcome and fluid management in critically ill patients. J Formos Med Assoc. 2015;114(12):1187–96.
100. Curtis KA, Waikar SS, Mc Causland FR. Higher NT-proBNP levels and the risk of intradialytic hypotension at hemodialysis initiation. Hemodial Int. 2024;28(1):77–84.
101. Barberato SH, Mantilla DE, Misocami MA, Gonçalves SM, Bignelli AT, Riella MC, et al. Effect of preload reduction by hemodialysis on left atrial volume and echocardiographic Doppler parameters in patients with end-stage renal disease. Am J Cardiol. 2004;94(9):1208–10.
102. Vignon P, Allot V, Lesage J, Martaillé JF, Aldigier JC, François B, et al. Diagnosis of left ventricular diastolic dysfunction in the setting of acute changes in loading conditions. Crit Care. 2007;11(2):R43.
103. Ommen SR, Nishimura RA, Appleton CP, Miller FA, Oh JK, Redfield MM, et al. Clinical utility of doppler echocardiography and tissue doppler imaging in the estimation of left ventricular filling pressures. Circulation. 2000;102(15):1788–94.
104. Allyn J, Allou N, Dib M, Tashk P, Desmard M, Dufour G, et al. Echocardiography to predict tolerance to negative fluid balance in acute respiratory distress syndrome/acute lung injury. J Crit Care. 2013;28(6):1006–10.
105. van der Sande F, Cheriex E, van Kuijk W, Leunissen K. Effect of dialysate calcium concentrations on intradialytic blood pressure course in cardiac-compromised patients. Am J Kidney Dis. 1998;32(1):125–31.
106. Pun PH, Horton JR, Middleton JP. Dialysate calcium concentration and the risk of sudden cardiac arrest in hemodialysis patients. Clin J Am Soc Nephrol. 2013;8(5):797–803.
107. Kelly YP, Sharma S, Mothi SS, McCausland FR, Mendu ML, McMahon GM, et al. Hypocalcemia is associated with hypotension during CRRT: a secondary analysis of the acute renal failure trial network study. J Crit Care. 2021;65:261–7.
108. Scholze A, Maier A, Stocks F, Karamohamad F, Vetter R, Zidek W, et al. Sustained increase of extracellular calcium concentration causes arterial vasoconstriction in humans. J Hypertens. 2005;23(11):2049–54.
109. der Sande Kooman FMJP, Konings CJ, Leunissen KML. Thermal effects and blood pressure response during postdilution hemodiafiltration and hemodialysis. J Am Soc Nephrol. 2001;12(9):1916–20.
110. Maggiore Q, Pizzarelli F, Santoro A, Panzetta G, Bonforte G, Hannedouche T, et al. The effects of control of thermal balance on vascular stability in hemodialysis patients: results of the European randomized clinical trial. Am J Kidney Dis. 2002;40(2):280–90.
111. Larkin JW, Reviriego-Mendoza MM, Usvyat LA, Kotanko P, Maddux FW. To cool, or too cool: is reducing dialysate temperature the optimal approach to preventing intradialytic hypotension? Semin Dial. 2017;30(6):501–8.
112. Mahida BH, Dumler F, Zasuwa G, Fleig G, Levin NW. Effect of cooled dialysate on serum catecholamines and blood pressure stability. Trans Am Soc Artif Intern Organs. 1983;29:384–9.
113. Selby NM, McIntyre CW. A systematic review of the clinical effects of reducing dialysate fluid temperature. Nephrol Dial Transplant. 2006;21(7):1883–98.
114. Edrees FY, Katari S, Baty JD, Vijayan A. A pilot study evaluating the effect of cooler dialysate temperature on hemodynamic stability during prolonged intermittent renal replacement therapy in acute kidney injury. Crit Care Med. 2019;47(2):e74-80.
115. Rokyta R, Matejovic M, Krouzecky A, Opatrny K, Ruzicka J, Novak I. Effects of continuous venovenous haemofiltration-induced cooling on global haemodynamics, splanchnic oxygen and energy balance in critically ill patients. Nephrol Dial Transplant. 2004;19(3):623–30.
116. Robert R, Méhaud JE, Timricht N, Goudet V, Mimoz O, Debaene B. Benefits of an early cooling phase in continuous renal replacement therapy for ICU patients. Ann Intensive Care. 2012;2(1):40.
117. Ospina-Tascón GA, Teboul JL, Hernandez G, Alvarez I, Sánchez-Ortiz AI, Calderón-Tapia LE, et al. Diastolic shock index and clinical outcomes in patients with septic shock. Ann Intensive Care. 2020;10(1):41.
118. da Horapassos R, Coelho FO, Caldas JR, dosde Santos GalvãoMelo EB, de Carvalho Farias AM, Messeder OHC, et al. Predicting intradialytic hypotension in critically ill patients undergoing intermittent hemodialysis: a prospective observational study. Intensive Care Med Exp. 2024;12(1):82.
119. Hamzaoui O, Teboul JL. Importance of diastolic arterial pressure in septic shock: PRO. J Crit Care. 2019;51:238–40.
120. Evans L, Rhodes A, Alhazzani W, Antonelli M, Coopersmith CM, French C, et al. Surviving sepsis campaign: international guidelines for management of sepsis and septic shock 2021. Intensive Care Med. 2021;47(11):1181–247.
121. Chaudhuri D, Nei AM, Rochwerg B, Balk RA, Asehnoune K, Cadena R, et al. 2024 Focused update: guidelines on use of corticosteroids in sepsis, acute respiratory distress syndrome, and community-acquired pneumonia. Crit Care Med. 2024;52(5):e219–33.
122. Carrara M, Ferrario M, Bollen Pinto B, Herpain A. The autonomic nervous system in septic shock and its role as a future therapeutic target: a narrative review. Ann Intensive Care. 2021;11(1):80.
123. Toner A, Whittle J, Ackland GL. Autonomic dysfunction is the motor of chronic critical illness. In: Annual update in intensive care and emergency medicine 2013. Berlin, Heidelberg: Springer Berlin Heidelberg; 2013. p. 199–209.
124. Hilz MJ, Liu M, Roy S, Wang R. Autonomic dysfunction in the neurological intensive care unit. Clin Auton Res. 2019;29(3):301–11.
125. Akada S, Fagerlund MJ, Lindahl SGE, Sakamoto A, Prabhakar NR, Eriksson LI. Pronounced depression by propofol on carotid body response to CO2 and K+-induced carotid body activation. Respir Physiol Neurobiol. 2008;160(3):284–8.
126. Eriksson LI, Sato M, Severinghaus JW. Effect of a vecuronium-induced partial neuromuscular block on hypoxic ventilatory response. Anesthesiology. 1993;78(4):693–9.
127. Wieske L, Chan Pin Yin DRPP, Verhamme C, Schultz MJ, van Schaik IN, Horn J. Autonomic dysfunction in ICU-acquired weakness: a prospective observational pilot study. Intensive Care Med. 2013;39(9):1610–7.
128. Schmidt H, Hoyer D, Wilhelm J, Söffker G, Heinroth K, Hottenrott K, et al. The alteration of autonomic function in multiple organ dysfunction syndrome. Crit Care Clin. 2008;24(1):149–63.
129. Shaffer F, Ginsberg JP. An overview of heart rate variability metrics and norms. Front Public Health. 2017;5:258.
130. Mazzeo AT, la Monaca E, di Leo R, Vita G, Santamaria LB. Heart rate variability: a diagnostic and prognostic tool in anesthesia and intensive care. Acta Anaesthesiol Scand. 2011;55(7):797–811.
131. de Castilho FM, Ribeiro ALP, Nobre V, Barros G, de Sousa MR. Heart rate variability as predictor of mortality in sepsis: a systematic review. PLoS One. 2018;13(9):e0203487.
132. Schmidt H, Müller-Werdan U, Hoffmann T, Francis DP, Piepoli MF, Rauchhaus M, et al. Autonomic dysfunction predicts mortality in patients with multiple organ dysfunction syndrome of different age groups. Crit Care Med. 2005;33(9):1994–2002.
133. Park S, Kim WJ, Cho NJ, Choi CY, Heo NH, Gil HW, et al. Predicting intradialytic hypotension using heart rate variability. Sci Rep. 2019;9(1):2574.
134. Pinto Lima A, Beelen P, Bakker J. Use of a peripheral perfusion index derived from the pulse oximetry signal as a noninvasive indicator of perfusion. Crit Care Med. 2002;30(6):1210–3.

135. Lima A, Bakker J. Noninvasive monitoring of peripheral perfusion. Intensive Care Med. 2005;31(10):1316–26.
136. dos Santos DM, Quintans JSS, Quintans-Junior LJ, Santana-Filho VJ, da Cunha CLP, Menezes IAC, et al. Association between peripheral perfusion, microcirculation and mortality in sepsis: a systematic review. Brazilian Journal of Anesthesiology (English Edition). 2019;69(6):605–21.
137. Tapar H, Karaman S, Dogru S, Karaman T, Sahin A, Tapar GG, et al. The effect of patient positions on perfusion index. BMC Anesthesiol. 2018;18(1):111.
138. Guimarães LB, Guimarães CM, Carraro Junior H, Assreuy Filho J, de Menezes IAC. Peripheral perfusion response to semiorthostatic stress: a simple method for assessing autonomic dysfunction in sepsis? Crit Care Sci. 2024. https://doi.org/10.62675/2965-2774.20240090-en.
139. Beurton A, Teboul JL, Gavelli F, Gonzalez FA, Girotto V, Galarza L, et al. The effects of passive leg raising may be detected by the plethysmographic oxygen saturation signal in critically ill patients. Crit Care. 2019;23(1):19.
140. Klijn E, Groeneveld ABJ, van Genderen ME, Betjes M, Bakker J, van Bommel J. Peripheral perfusion index predicts hypotension during fluid withdrawal by continuous veno-venous hemofiltration in critically ill patients. Blood Purif. 2015;40(1):92–8.
141. Mostafa H, Shaban M, Hasanin A, Mohamed H, Fathy S, Abdelreheem HM, et al. Evaluation of peripheral perfusion index and heart rate variability as early predictors for intradialytic hypotension in critically ill patients. BMC Anesthesiol. 2019;19(1):242.
142. de los Reyes VAA, Fuertinger DH, Kappel F, Meyring-Wösten A, Thijssen S, Kotanko P. A physiologically based model of vascular refilling during ultrafiltration in hemodialysis. J Theor Biol. 2016;390:146–55.
143. Mitsides N, Pietribiasi M, Waniewski J, Brenchley P, Mitra S. Transcapillary refilling rate and its determinants during haemodialysis with standard and high ultrafiltration rates. Am J Nephrol. 2019;50(2):133–43.
144. Baldwin I, Maeda A, Bellomo R, See E. Haematocrit monitoring and blood volume estimation during continuous renal replacement therapy. Aust Crit Care. 2024;37(4):632–7.
145. Rabi R, Alsaid RM, Matar AN, Dawabsheh Y, Abu GD. The role of serum albumin in critical illness, predicting poor outcomes, and exploring the therapeutic potential of albumin supplementation. Sci Prog. 2024. https://doi.org/10.1177/00368504241274023.
146. Atrash AK, de Vasconcellos K. Low albumin levels are associated with mortality in the critically ill: a retrospective observational study in a multidisciplinary intensive care unit. South Afr J Crit Care. 2020;36(2):74–9.
147. Nakamoto H, Honda N, Mimura T, Suzuki H. Hypoalbuminemia is an important risk factor of hypotension during hemodialysis. Hemodial Int Symposium on Home Hemodial. 2006;10(Suppl 2):S10-5.
148. Fortin PM, Bassett K, Musini VM. Human albumin for intradialytic hypotension in haemodialysis patients. Cochrane Database Syst Rev. 2010;11:CD006758.
149. Knoll GA, Grabowski JA, Dervin GF, O'Rourke K. A randomized, controlled trial of albumin versus saline for the treatment of intradialytic hypotension. J Am Soc Nephrol. 2004;15(2):487–92.
150. van der Sande FM, Kooman JP, Barendregt JNM, Nieman FHM, Leunissen KML. Effect of intravenous saline, albumin, or hydroxyethylstarch on blood volume during combined ultrafiltration and hemodialysis. J Am Soc Nephrol. 1999;10(6):1303–8.
151. Rostoker G, Griuncelli M, Loridon C, Bourlet T, Illouz E, Benmaadi A. A pilot study of routine colloid infusion in hypotension-prone dialysis patients unresponsive to preventive measures. J Nephrol. 2011;24(2):208–17.
152. Macedo E, Karl B, Lee E, Mehta RL. A randomized trial of albumin infusion to prevent intradialytic hypotension in hospitalized hypoalbuminemic patients. Crit Care. 2021;25(1):18.
153. Clark E, McIntyre L, Watpool I, Kong JWY, Ramsay T, Sabri E, et al. Intravenous albumin for the prevention of hemodynamic instability during sustained low-efficiency dialysis. A randomized controlled feasibility trial. (the SAFER-SLED study). Ann Intensive Care. 2021;11(1):174.
154. Janeway CA, Gibson ST, Woodruff LM, Heyl JT, Bailey OT, Newhouser LR. Chemical, clinical, and immunological studies on the products of human plasma fractionation. vii. concentrated human serum albumin 123. J Clin Invest. 1944;23(4):465–90.
155. Frenette AJ, Bouchard J, Bernier P, Charbonneau A, Nguyen LT, Rioux JP, et al. Albumin administration is associated with acute kidney injury in cardiac surgery: a propensity score analysis. Crit Care. 2014;18(6):602.
156. Lee EH, Kim WJ, Kim JY, Chin JH, Choi DK, Sim JY, et al. Effect of exogenous albumin on the incidence of postoperative acute kidney injury in patients undergoing off-pump coronary artery bypass surgery with a preoperative albumin level of less than 4.0 g/dl. Anesthesiology. 2016;124(5):1001–11.
157. Wiedermann CJ, Dunzendorfer S, Gaioni LU, Zaraca F, Joannidis M. Hyperoncotic colloids and acute kidney injury: a meta-analysis of randomized trials. Crit Care. 2010;14(5):R191.
158. Rochwerg B, Alhazzani W, Gibson A, Ribic CM, Sindi A, Heels-Ansdell D, et al. Fluid type and the use of renal replacement therapy in sepsis: a systematic review and network meta-analysis. Intensive Care Med. 2015;41(9):1561–71.
159. Shehabi Y, Balachandran M, Al-Bassam W, Bailey M, Bellomo R, Bihari S, et al. Postoperative 20% albumin infusion and acute kidney injury in high-risk cardiac surgery patients. JAMA Surg. 2025;160(8):835.
160. Callum J, Skubas NJ, Bathla A, Keshavarz H, Clark EG, Rochwerg B, et al. Use of intravenous albumin. Chest. 2024;166(2):321–38.
161. Schortgen F, Soubrier N, Delclaux C, Thuong M, Girou E, Brun-Buisson C, et al. Hemodynamic tolerance of intermittent hemodialysis in critically ill patients: usefulness of practice guidelines. Am J Respir Crit Care Med. 2000;162(1):197–202.
162. Malbrain MLNG, Marik PE, Witters I, Cordemans C, Kirkpatrick AW, Roberts DJ, et al. Fluid overload, de-resuscitation, and outcomes in critically ill or injured patients: a systematic review with suggestions for clinical practice. Anestezjol Intens Ter. 2014;46(5):361–80.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.